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Service-based Production Planning and Control of Cyber-Physical Production Systems

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Abstract

Industrial production is facing major challenges with regard to flexibility and productivity during the manufacturing process. Due to the dynamic of product lifecycles, the number of product variants manufactured in the same production environment is continuously increasing. This paper explains the principles and the necessity for service-based planning and control of cyber-physical production systems (CPS) within a dynamic I4.0 environment. Furthermore, the paper presents the results of a public research project and describes the architecture and functionality of a derived CPS scheduling service. The service has been tested in real-life production in a lens manufacturing and show the monetary benefit of a CPS scheduling.

Keywords: Production scheduling, Cyber-Physical Production Systems, Service-based

1 Introduction

In August 2015, nearly 5.4 million of 42.89 million German employees worked in manufacturing companies, which are in essence small and medium-sized enterprises with less than 250 employees and 50 Mio. EUR turnover (Statistisches Bundesamt, 2015). After a GDP growth up to 3,75% in the years from 2000-2008, the economic turbulences between 2008-2010 and the resulting down-/up-swing, economic turbulences as well as home-made

challenges will lead to major challenges in the upcoming years (Spath et. Al., 2013). The German manufacturing focus is clearly set on high-end premium products instead of low and medium-cost goods (Brecher, 2012). However, this interferes with the pressure on prices, costs and delivery times by global markets combined with unpredictable dynamics in all business areas (Jeschke, 2014). In order to compete in these conditions, manufacturing companies have to become more efficient, flexible and responsive to market changes (Abele & Reinhart, 2011). Politicians in Germany became aware of these challenges and funded research in this area five years ago. As a result, the key to meet these challenges is regarded in the use of information and communication technologies (ICT) within the manufacturing domain (Kagermann, 2013). With new technologies like the “Internet of Things” (IOT) and services in general (Kopetz, 2011), a paradigm change has started in the manufacturing industry and the German term “Industrie 4.0” or “Industry 4.0” (I4.0) became popular. This paper focuses on production planning and control within the I4.0 environment and its impact on the way of scheduling manufacturing environments.

2 Industry 4.0 and cyber-physical systems

I4.0 is a combination of the Computer Integrated Manufacturing (CIM) and Lean Management, trying to combine the benefits of both (Broy, 2010), (Schuh & Stich, 2014). From a technology perspective, the Internet of Things is the main driver of I4.0. IoT describes a vision, in which each device has its own IP address (Bauernhansl, 2015). These devices become smarter and are able connect with their surrounding environment. Therefore, these systems are able to communicate with humans, machines and any other compatible devices. Consequently, IoT benefits could be the reduction of energy costs, more comfort, healthcare support and higher flexibility (Bullinger & Hoppel, 2007).

The technology for IoT is already available, cheap and powerful (Atzori & Iera & Morabito, 2010) similar to the development of smartphones. Hence, IoT is getting more and more interesting for manufacturing companies (Yang et. al., 2014). Modern plants consist of various machines and industrial manufacturing equipment like turning or milling machines, assembly lines etc., which are more or less smart. I4.0, respectively IoT, tries to integrate their environment vertically as well as in a horizontal way in order to exchange information. These devices, so-called cyber-physical systems (CPS), are main enablers for flexibility and productivity in the I4.0 manufacturing environment (El Kadiri, 2015). CPS consists of embedded systems with the ability to communicate, preferably via internet technologies like web services (Schuh et. Al., 2014). Hence, CPS are more than just an interface due to their ability to represent relevant knowledge about their physical reality and autonomous computing capacity for analysis and interpretation of the data (Reinhart et. Al., 2015). Moreover, a CPS can interact with another CPS beyond their own system boundaries. Therefore, CPS must be designed for cross-linking (Lee, 2008). This attribute requires broad networking abilities, which are presently unavailable.

This paper focuses on I4.0 CPS manufacturing in the context of I4.0 production scheduling and control. Hence, the focus is not set on topics like vertical and horizontal integration and impacts of I4.0 on business models or production systems.

Following these assumptions, the question arises how scheduling software must operate to fulfil these demands. Due to the new technologies, the production planning and control software has to work in real-time in order to deal with CPS equipment reporting the own condition at any time.

3 Call for action

Due to the outlined changes in terms of dynamics, real-time data and complexity, current software for production planning and control has limited applicability within I4.0 environment (Klein et. Al., 2014). The major challenges can be summarized as following:

1. Rigid, respective not service-based, architectures and therefore lack of adaptability, versatility and scalability of these mostly proprietary systems
2. Time, cycle- and event-driven operations with focus on the support of manual production planning and control activities
3. Insufficient real-time capabilities which results in hourly or daily based scheduling batch runs
4. Scheduling of only one resource (e.g. machine, work place or employee) instead of a simultaneous scheduling of multiple resources

In contrast to the background of the I4.0 conditions of real-time production planning and control, the following requirements apply to appropriate CPS scheduling software:

1. Service-based architecture with high adaptability and scalability
2. Service-driven operations
3. Real-time production planning and control
4. Simultaneous backlog-free, multi-resource scheduling for machine, work place or employee, tool, material, etc.

Based on these requirements, a service-based multi-resource production planning and control software for I4.0 environments has been designed, developed, prototypical applied and validated in real-world cyber-physical production environments.

4 CPS scheduling service

The following chapters describe the structure and functionality of a CPS scheduler. The concept and prototype was derived in the 2012-2015 carried out research project CyProS funded by the German Federal Ministry of Research and Technology (BMBF) encompassing 19 industrial enterprises and research institutes (BMBF Industrie 4.0, 2015). Main aim of CyProS was the development of different CPS and the methodology of using them in real life

production environments. Here, one of the scopes was to evaluate the benefits of CPS regarding the enhancement of productivity and flexibility.

4.1 Data and interfaces

All production planning and control system use more or less static master data and more or less highly dynamic data like e.g. production orders or shopfloor bookings (Kropp, 2014). That is similar in the I4.0 context of CPS scheduling and capacity planning, where the following data is mandatory:

1. Master data
 - Users, rights and roles for users of the CPS scheduling service
 - Resource master data for work places, machines or employees like ID, name etc.
 - Scheduling parameters like scheduling type, frozen zones etc.
2. Dynamic data
 - Customer orders, order confirmations or demands
 - Procurement orders or demands
 - Manufacturing orders
 - Working plans per manufacturing order with operations, standard times, allocated resources etc.
 - Real data with reference to an operation via e.g. manual shopfloor data collection
 - Real data with reference to a resource via e.g. machine data collection per time and attendance collection
 - Material availabilities, stock levels, bill-of-materials for stock articles etc.
 - Shifts, shift models or capacities per resource

The CPS scheduling services was designed to manage the depicted data stand-alone and/or by horizontal and/or vertical integrations to surrounding IT systems. Hence, the CPS scheduling service can be implemented in heterogeneous environments, which is often the case, especially in small and medium-sized enterprises. On the other hand, big companies can easily integrate their existing ERP or MRP and special purpose IT systems by using the pre-defined interface(s) for horizontally and vertically integrated data flows on the basis of:

1. File-based interfaces with ASCII, CSV, XML or IDoc files
2. SQL-based interfaces with transfer databases
3. Web service using REST or SOAP technology
4. OPC UA

The interfaces 1 and 2 are used more often to connect legacy systems. However, communication via web services has become a major precondition in I4.0 CPS environment (Berlak, 2015), (Franke et. al., 2014). Based on these four interfacing technologies, almost every actual or future IT system can be integrated with the CPS scheduling service (Reinhart, 2013)

4.2 Architecture for the scheduling service

Based on the derived call for action presented in chapter 3, the main conceptual approach was to derive a service-based architecture with high adaptability and scalability in order to enable real-time production planning and control with simultaneous backlog-free multi-resource scheduling. Hence, the IT architecture consists of different layers and technologies. The CPS scheduling service has been designed and implemented in Java EJB. The underlying service-oriented (SaaS) client-server architecture bases on the JBoss Application Server. Using the Hibernate framework, almost any SQL database can be used for storing the scheduling data. Evaluations or printable reports for users of the CPS scheduling service are created using open-source JasperSoft iReports. Thanks to Java and the derived architecture, any JRE supported hardware, e.g. PC, IndustrielPC, Raspberry Pie, mobile device etc. or operating system, e.g. MS Windows, Linux, etc., can be used for running the CPS scheduling service. By iterative development applying the Rational Unified Process (RUP), permanent testing and the Java EJB technology, the CPS scheduling service has been implemented very effectively and efficiently. In summary, the CPS scheduling service architecture is versatile, future-proof, service-oriented and scalable (Broy, 2013). The main functions, relations and interfaces of the CPS scheduling service architecture between the shopfloor and office level are depicted in Figure 1.

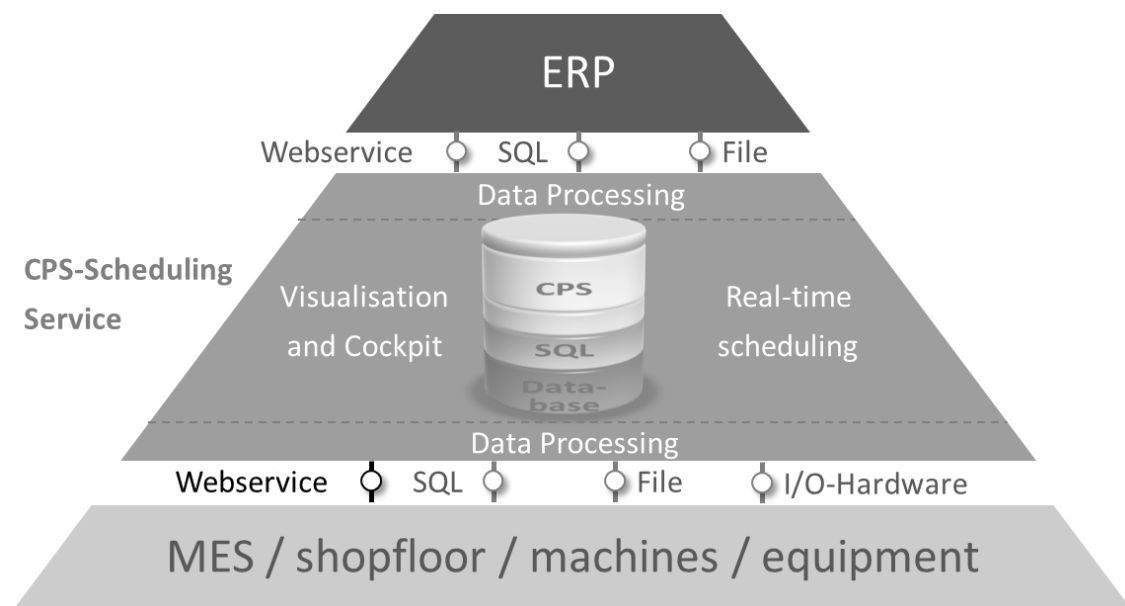


Figure 1: Architecture of the CPS scheduling services and its environment (Reinhart, 2015)

Based on Figure 1, the necessary scheduling data, as well as the interface between shopfloor and ERP level, are describe within the next chapter.

4.3 CPS scheduling service

The CPS scheduling service consists of three components (see Figure 1):

1. The data processing service
2. The real-time scheduler
3. A graphical user interface

The real-time scheduler is based on a backlog-free planning algorithm for scheduling customer and manufacturing orders with finite capacities. In contrast to today's ERP and MRP system scheduling with infinite capacities backward or forward, backlog-free means that the scheduler cannot schedule in the past. Instead, the actual point in time is the earliest possible start date for an operation. This enables realistic schedules, which is also a benefit of I4.0 CPS environments. Furthermore, the term "finite capacities" means that all scheduled resource like e.g. employees, machines, workplaces or tools have at least one valid shift allocated at all times (e.g. night shift 22:00-06:00 with pause from 01:00-01:30). Shifts and shift models can either be imported via interface or manually administered in a calendar.

Derived as need for action (see chapter 3), a scheduler for I4.0 CPS should run event-triggered as a service, rather than manually provoked or on a scheduled basis (e.g. every day or hour). This means that the scheduler reacts dynamically on changes and adjusted to the real situation. When a machine brakes down for example, it sends this information via web service interface (see chapter 4.2). The scheduler changes its capacity to "not available" and re-schedules all orders and operations automatically. However, in order to meet the challenges of industrial practice, a manual intervention of a human scheduler was built in the graphical user interface.

On opening the graphical planning board, all relevant master and dynamic data are processed in-memory in order to derive a realistic view on the production. The human scheduler can see deviations for orders immediately based on traffic light visualization. Furthermore, planned throughput times, problems and bottlenecks are presented as well. On that basis, the human scheduler can make changes to the plans by what-if-scenarios. Either manually per drag and drop movement of orders and operations or automatic optimization algorithms. These changes are not directly processed to the ERP and MRP system. The submission of scheduled start and end dates is released by saving the actual plan. In case that the plan is not sufficient for the human scheduler, he can undo the changes.

The graphical user interface (GUI) of the CPS-scheduler is depicted in Figure 2. It is separated in two areas: The upper area consists of tables for customer and manufacturing orders and operations. The bottom area shows a graphical Gantt chart graphical.

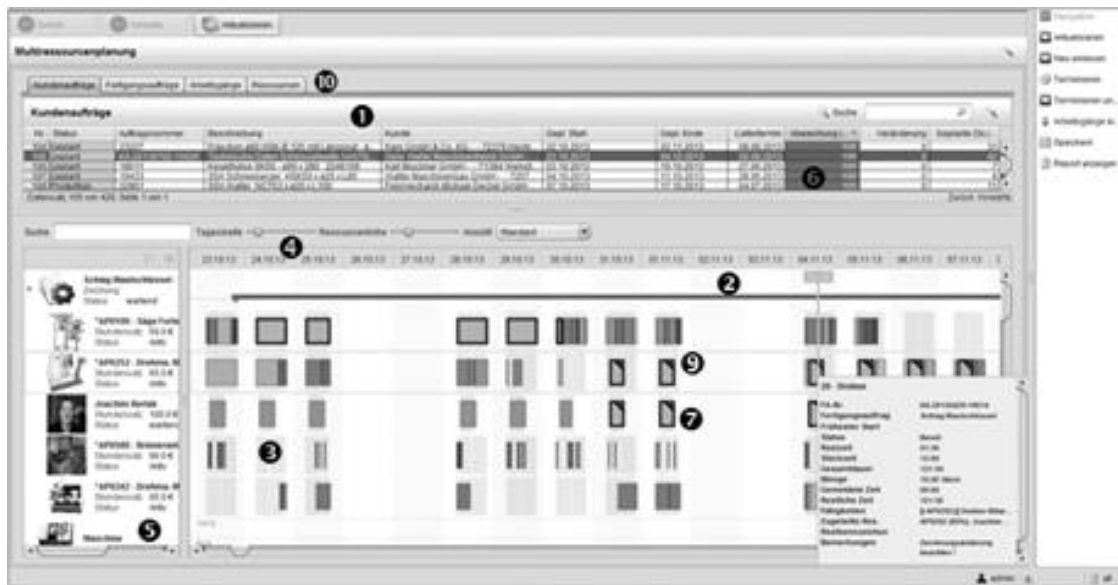


Figure 2: Graphical user interface of the CPS-scheduler

The main functions and items of the scheduler are depicted as follows:

1. Tables with customer or manufacturing orders, operations and resources:

The tables, respectively the columns, can be sorted, moved and filtered upon customer's request including a full-text search. The tables are updated in real-time, e.g. the status information according to as-is data from the shopfloor.

2. Flow of an order through production:

The sequence of a single order or an n-tier order tree is shown in the Gantt chart by double-clicking one of the table entries. Here, the sequences of operations and allocated resources as well as dependencies are clearly represented: every row represents a resource and the highlighted white box shows the associated operation of a selected order.

3. Capacity proposal:

The available capacity according to the assigned shifts and shift models is presented as coloured boxes. Lime represents available capacity and white/yellow unavailable (e.g. Saturday or Sunday).

4. Variation in time:

The Y-axis represents the time, the scale can be adjusted by sliders or mouse wheel.

5. Resource hierarchy:

Using grouping functions, types and capabilities, various organization structures within the CPS can be defined. When required, the structures can be scaled down or upwards.

6. Adherence to delivery dates and impact visualization:

In industrial manufacturing, the adherence to promised delivery dates is one of the major competitive advantages. In order to recognize delayed orders at an early stage, the CPS scheduler calculates the deviation between delivery date and scheduled end date and depicts the result with a customizable coloured traffic light: red means too late for various days, green means right on time and yellow represents too early. This list represents a to-do list for the human scheduler to take countermeasures like external processing of orders or operations, re-scheduling operations to another resource or talking to the customer and changing delivery dates. Please note that the result is strongly related to the type of scheduling: forward scheduling tries to start orders respectively operations as soon as possible with the effect that orders can be finished before the confirmed delivery date (yellow deviance). Whereas backward scheduling plans just-in-time to the delivery date (green deviance) with the effect that capacities could be idle or suboptimal utilized. Manual or automatic schedules always change the plans. In order to visualize the effect of a new schedule, a coloured up-/downward arrow appears: red means decline about various days, green represents improvement. Hence, the effect of schedules can be judged, which is very important for what-if-scenarios.

7. Simulation of dissent capacity scenarios:

An inherent question in production scheduling is, whether an additional shift or capacity is suitable for delivering orders right on-time and whether the cost-benefit ratio is appropriate for doing so. These challenges can be answered (ether: faced) by manual or automatic capacity adjusting and the effect will be visualized (see 6).

8. Save and undo function:

As long as the actual schedule is not saved, the manual schedules and what-if-scenarios can be reverted by the undo function, loading the last saved state. However, these plan are aligned with the actual situation within the CPS according to the as-is data.

9. Notes:

With the note feature, human schedulers can comment e.g. planning situations, orders and decisions. This makes it easier to track and communicate plans.

10. Operation queue:

The main scheduling result is a plan which can be viewed in the Gantt chart. However, a table view is more suitable and processible e.g. for shopfloor employees as well as machines. This list contains the orders or operations of a resource, sorted by the scheduled start and end dates.

Furthermore scheduling functions encompass the release of orders to the scheduler, splitting of orders and/or operations, fixation of orders and/or operations and a frozen-zone.

5 Application and validation

The CPS scheduling services has been tested in real-life production environments in order to judge its suitability and benefits for I4.0 CPS environments. The following application for lens manufacturing at Satisloh AG in a unique manufacture-to-order environment is described here as a showcase.



Figure 3: Validation of the CPS-planning service in lens manufacturing

Satisloh AG is a Swiss-based machine and equipment manufacturer for ophthalmic and precision optics manufacturing. There is a so-called demo-lab located at their site in Wetzlar (Germany). This demo-lab is a real manufacturing site with all necessary equipment to produce lenses in industrial conditions as showcase for customers and for the Satisloh internal lens production. Here, up to twelve process steps like generating, edging, coating etc. are carried out by machines linked together by conveyor belts with a throughput time of 2-4 hours. Hence, this is the ideal environment to test the CPS scheduler under real-world conditions according to the following scenario.

To validate the CPS-planning services in practice, the following scenario was developed. The demonstration lab for spectacle lens manufacturing (Figure 3) includes three production steps. It starts with glass blanks on a tray with each having a unique order number in form of a barcode.

The process starts by inserting the trays in the transfer device, the conveyor belt transports the trays to the appropriate machines. Every machine reads the barcode and receives the order number from a central Lab Management System (LMS). The LMS sends the machining programs and process parameters to the particular machine. The CPS-planning service receives the information about the machine status, the job number as well as the actual process from the spectacle lens machines via REST web services. The web service is on the same server as the Lab Management System (LMS) located and communicates also with it via REST web service in real time.

The following sequence from the communication shows, which information are transmitted in the CPS test scenario:

At first, the transfer of ten orders with the reference data from the LMS and a concurrent processing of the corresponding processes within the CPS-planning service need to be started. The second step is to receive actual feedback from the machinery and equipment, which order process starts/ends, the equipment status and process data. Ultimately, a disturbance of machinery for 120 second will be simulated. Hence, redundant machinery is necessary for the meaningful implementation of the rescheduling in CPS-planning service.

Requirements, which the CPS-planning service needs to meet, are the following: detecting of machine malfunctions in real-time, rescheduling of the following orders or processes to the second machine and re-use of the disturbed machine.

The scenario described above was carried out in the demonstration lab over 50 times and has been tested at the customer day in live operations. The evaluation of the test scenarios revealed a response in almost real time to a machine disturbance. On average, the processing speed from the beginning of the disturbance to the processing in the database is smaller than 0.5-1 second. A threshold of 10 seconds avoids rescheduling of errors caused by short-time process and machine disturbances. The automatic rescheduling of CPS-planning services and the dissemination of the "command" over a REST web service to the conveyor belt lasted approximately two seconds. It could be determined, that the CPS-planning service can act in a time range of 2-4 seconds by rescheduling.

The monetary benefits can be shown in the following opportunity cost calculation: Without a CPS-planning service, costs arise by an hourly rate of 100 EUR by the waiting time of 3.33 EUR per disturbance. With a CPS-planning service, the waiting time is significantly reduced with the rescheduling after a 10 seconds threshold time. In consequence, the manufacturing cost saving accounts for 65.384 EUR, under the assumption of ten errors per shift and 220 working days.

6 Conclusion and discussion

It can be stated that the real-time CPS scheduling service is rather different to a conventional production planning system. The major difference is the event driven rescheduling of the production planning. This approach is possible with the straight-lined architecture, fitting interfaces between the shop floor levels and the production data.

7 Summary and outlook

The identification of unforeseen events in the production and the timely reaction on those is becoming increasingly important for companies. The real-time scheduling service for the planning and control of cyber-physical systems is an enabler for more flexibility in the manufacturing. Therefor essential is a multiple resources scheduling and a service-based real-time architectures. To develop the necessary production data and interfaces for production control is a basis for the use of service-based production planning in context of discrete manufacturing, in this article an approach to develop the basic components of the architecture is presented. So, compared to existing applications production planning in the context of

service based architectures, the level of abstraction is concrete and a practical way. The core of the solution includes requirements of the scheduling and combines them with the new possibility of the cyber-physical production systems in the architecture. Its example application within in real-live lens manufacturing demonstrates that scheduling services can contribute to cost savings by reactive planning.

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